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INVESTIGATION OF THE PHENOMENA OF RAIN EROSION AT SUBSONIC AND SUPERSONIC SPEEDS

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BELL AEROSYSTEMS COMPANY

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RESEARCH AND TECHNOLOGY DIVISION
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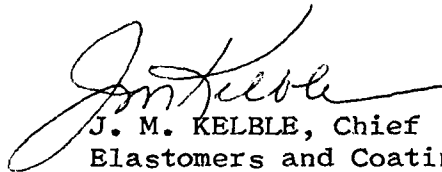*BUFFALO, NEW YORK, USA*

FOREWORD

This report was prepared by Mr. Norman E. Wahl of Bell Aerosystems Company, Buffalo, New York. This was initiated under Project 7340, "Nonmetallic and Composite Materials", Task 734007 "Coatings for Energy Utilization, Control and Protective Functions". The work was administered under Contract No. AF 33(657)-8741 for the Nonmetallic Materials Division, Air Force Materials Laboratory, Research and Technology Division with Lt. George F. Schmitt, Jr. acting as project monitor. Manuscript release by the author September 1965 for publication as an RTD Technical Report.

This report covers work conducted from January 1965 to September 1965.

This technical report has been reviewed and is approved.

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ABSTRACT

A comprehensive state-of-the-art survey in the field of rain erosion protection, evaluation and simulation has been completed. Past efforts in all phases of rain erosion research, both subsonic and supersonic are reviewed. Descriptions of evaluation facilities now in operation and summaries of past materials research are also included.

Recommendations for the improvement of laboratory simulation of high speed rain erosion protection techniques and the direction for new materials development are indicated.

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I. INTRODUCTION

Erosion by rain of the exterior of high speed aircraft during
flight was observed shortly after World War II on all-weather
fighter aircraft capable of flying at speeds over 400 mph. The
aluminum leading edges of wings and the glass reinforced plastic
nose radomes were particularly susceptible to this form of degrada-
tion.

Actual flight tests to determine the severity of this phenom-
enon of rain erosion were carried out by the United States Air Force
and by Cornell Aeronautical Laboratory, and it was established that
aluminum leading edges and plastics exhibited serious erosion after
exposure to rainfall of moderate intensity at flight speeds approach-
ing 500 mph. These detailed studies are outlined in Refs. 1 and 2
reports.

Inasmuch as this problem originally arose with military air-
craft, the US Air Force initiated research studies on the problem
at Wright Air Development Center, which have been reported by Ramke
& Long, Ref. 3. Under sponsorship of the Air Force, Dr. Engel at
the National Bureau of Standards was very active in investigating
the mechanics of rain erosion based on theoretical considerations,
Refs. 4 thru 17.

Dittman and Holmes of Convair, San Diego, Ref. 18 and 19, have
studied erosion testing methods at supersonic speeds, and Beal, Lapp,
Stutzman and Wahl, Cornell Aeronautical Laboratory, Refs. 20 thru
27, have conducted experimental studies on the rain erosion resist-
ance of all types of materials.

Because of the shift of interest, emphasis has been placed on problems of space travel and the amount of research effort on rain erosion has been drastically reduced since 1960. Due, however, to the planned flight profile of supersonic systems, additional studies are being sponsored in this field.

II. CURRENT REQUIREMENTS FOR RAIN EROSION RESISTANT MATERIALS

The current Air Force requirements for materials for aerospace vehicles that would be resistant to rain erosion at subsonic and supersonic speeds includes non-metallic materials such as glazing for windows, ceramics, reinforced plastics, and coatings for radomes as well as metallic materials having mechanical strength, at high temperature, for structural components.

The general types of all-weather craft of interest and the anticipated materials requirements are outlined below.

A. Subsonic Aerospace Craft

1. Large plastic or ceramic airborne radomes with good electrical and structural properties with an ability to withstand 350°F and be resistant to rain erosion at speeds up to Mach 1 and flights through rain for periods totaling 300 hours.

2. Polymeric or elastomeric coatings of various colors that will protect the above radomes under same flight conditions.

B. Supersonic Aerospace Craft

Radomes that will have satisfactory mechanical and electrical properties with an ability to withstand 1500°F and be resistant to rain erosion at speeds up to Mach 6 for flight through rain for periods totaling 5 hours. Coatings or a thin protective device are required to meet these flight conditions.

C.   Advanced Missiles

Structural materials with high strength at 2500°F that will be resistant to rain erosion for periods up to 5 minutes at speeds up to Mach 8.

III. SUMMARY OF CURRENT TECHNOLOGY

A. Mechanism of Erosion

Although the mechanism by which erosion is produced by high
speed water drop impingement was not completely understood, Engel,
Refs. 4 and 5, in 1953 described the impact process and the magni-
tude of the impact pressures.

In a recent investigation (1961) Bowden and Brunton studied the
deformation of a solid when impacted by a liquid moving at super-
sonic speeds, Ref. 64. In this study a single water drop moving at
a velocity of 2240 ft/sec (Mach 2) was caused to impact a station-
ary target of polymethyl-methacrylate and high speed photographs
were taken of the initial impact, the flow of the water drop and
the manner in which stresses were developed in the clear polymer
during the course of the impact. Based upon these studies the de-
formation mechanism causing liquid impact damage was analyzed in
detail.

When a liquid drop collides with the planar surface of a solid,
(a) it exerts a localized pressure and (b) it flows out radially
around the central point of impingement. A typical pattern is
shown in Fig. 8, Ref. 4.

During the early stages of the collision between a liquid drop and the planar surface of a solid, maximum pressure exists in a ring around the central point of the collision. At the first instant of the collision, when the maximum pressure is highest, this pressure ring causes shear failure. The radius of the ring of maximum pressure increases and the value of the maximum pressure in the ring decreases with time until the radius of the circle of contact between the drop and the solid is about 0.6 of the original radius of the drop. Bowden and Tabor, Ref. 71, have described the mechanism of damage and have photographed a cross section of the polymethyl-methacrylate to show these ringed cracks.

An impinging liquid drop acts like an impinging solid sphere in exerting a localized pressure. However, for any given impingement velocity, the localized pressure exerted by an impinging liquid drop is never as great as that exerted by an impinging solid sphere. This is because part of the collision energy of an impinging drop is transformed into radial flow of the liquid of which it is composed. An impinging solid sphere can inflict damage only by exerting localized pressure; an impinging liquid drop can inflict damage both by the localized pressures that it exerts and by its radial flow. For this reason the use of lead shot or spheres of solid materials in simulating the liquid erosion phenomena has been unsuccessful.

The impact pressure that is produced by the collision of a liquid drop with the planar surface of a solid drives the liquid that is close to the solid surface radially outward around a central stagnation point. The flow velocity can become very high. In the case of a water drop colliding with a glass plate, the flow velocity has been found to approach ten times the value of the impingement velocity, for short times after the impact, Ref. 4.

The radially flowing liquid of an impinging drop exerts a shear stress on the surface of the solid over which it is running. The shear stress τ between layers of liquid in laminar flow is $\tau = \mu \frac{\partial v}{\partial z}$ where μ is the viscosity of the liquid, v is the velocity at which the liquid is moving, and z is the direction through the thickness of the liquid film. The layer of liquid molecules in direct contact with the surface of the solid has zero velocity but the velocity gradient is not zero and the shear stress is applied to the solid.

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If the radial flow of an impinging liquid drop runs over a surface protrusion, it exerts forces against the protrusion. Pressure exerted against the protrusion by the flowing liquid tends to move the protrusion along the planar surface of the solid and results in a shear stress at the base of the protrusion. The pressure exerted by the liquid also results in a turning moment that tends to bend the protrusion. The turning moment is the integrated product of the compressive force exerted by the liquid and the distance above the planar surface at the point where the force is applied. If the forces exerted by the rapid flow of liquid are large enough, or if the protrusion has a notable elevation above the planar surface, failure may occur. The protrusion may be bent over, or it may be broken off.

Based upon theoretical calculations, the radial flow of liquid was predicted to produce a shear stress of approximately 630 psi on the surface of a metal when the impact velocity between water drop and metal surface is 500 mi/hr, Ref. 22.

If a solid material is protected by a rubbery coating, the shear stress is exerted on the coating. In the case of thick resilient coatings, this stress will be dissipated mainly in deforming the upper layers of the coating by stretching the coating radially from the point of impact. In this manner, a thick coating will protect the adhesive bond between the coating and the substrate material. Thin coatings have reduced resilience and the shear stress will be transmitted without much loss in intensity to the adhesive bond itself. If the adhesive bond fails, the coating is no longer fastened to the substrate in the area where the failure occurs. The

impingement of additional water drops on this area causes the loosened rubbery coating to stretch. Permanent set will be introduced into the loosened spot of coating with a consequent increase in area of the coating over its original area at the time that the adhesive bond failed. The result is that the coating rises in a dome over this spot and the unsupported dome shaped coating is rapidly torn through by additional water drops that strike it, causing the protective coating to fail.

The next case to consider is that of the materials which depress under the water drop impact and which flow plastically under the compressive load and do not recover or return to their original state. This case for plastics and relatively soft metals such as 1100 **aluminum** is clearly described by Engel, Ref. 6 and Bowden and Tabor, Ref. 71.

When a water droplet impinges at high velocity with plastic or soft metals, the compressive stress which is developed exerts a shear, and the rapid radial wash of the water acts with this shear stress to stack the material up by plastic flow around the mouth of the crater that is produced. Where these pressure-raisers are active, the impact stress is much higher and the radial flow is more rapid. The process continues with the formation of lateral cracks and the breaking away of material as other drops impinge into the crater already formed, with subsequent rapid erosion of the material.

The last case to consider concerns those materials which do not depress upon high velocity impact with a water drop. Metals of high Brinell hardness and ceramics are in this category. It is thought that with these materials, work hardening or impact fatigue causes

a small imperfection in the surface to be removed, with the formation of small craters or pits. While it is possible that additional droplet impacts may serve both to work-harden and fracture the material at the bottom of these craters, the damage may be accomplished entirely by the shear stress that is exerted by the water flow. The shear stress that is exerted by the water flow, and the torque that it exerts against any surface irregularity that exists in the bottom surface or in the walls of the pit and that is restrained by the underlying material may open new cracks in the interior surface of the pit and/or widen cracks that already existed. These cracks will be progressively widened by subsequent water drop blows until a state is reached in which coherent pieces of metal or ceramic will be broken out between them. Bowden and Tabor, Ref. 71, page 490, have taken some excellent pictures showing failure pattern in metals and glass.

After a specific time, a point appears to be reached at which a burst of erosion craters suddenly nucleates in the material surface. This extensive nucleation of small craters may be the result of deepening of the many pits to the point that they can serve as pressure-raisers to the impinging drops, as well as of a general work-hardening of the surface. The entire surface then rapidly becomes covered with adjacent and then overlapping craters. If the water drop impingement is continued sufficiently long, the process of forming cracks on the bottom surface and on the walls of the pits and of breaking material away between the cracks will eventually result in erosion completely through a sheet of metal or fracture of a ceramic structure.

B. Factors Influencing Rain Erosion

It has been experimentally established that the major factors influencing the rate and extent of erosion damage to materials due to water drop impact are:

    1. Collision Velocity

    2. Water droplet size

    3. Time

    4. Design

1. Collision Velocity

The collision velocity between a water drop and a specific solid surface is the most important element governing the amount and rate of rain erosion damage.

The lower limit of collision velocity at which erosion damage of a given material occurs is a function of the drop size impacting the surface. There are no quantitative experimental data as to what this minimum velocity is for various types of materials. From actual flight data, it appears that with high strength aluminum alloys the practical threshold velocity is close to 400 mph for rainstorms of average intensity.

As an example of the dependence of collision velocity on the initiation of erosion, Honegger, Ref. 28, cites an experiment using mild steel in which this material was subjected to the same size and number of water drop impacts (215,000) at two collision velocities 280 mph (410 ft/sec) and 390 mph (575 ft/sec). At the

lower velocity, 280 mph, there was no sign of erosion of the steel surface; however, pitting due to erosion was quite pronounced at 390 mph.

Although Honegger did not find a numerical relation between impact velocity and the extent of erosion for the various metals and alloys, he prepared plots of the weight loss of various metals as a function of the impact velocity.

In experiments described by deHaller, Vater, and Brandenberger, Refs. 30 and 31, it is determined that the extent of rain erosion increased rapidly with increase of impact velocity and droplet size.

In the work of Hengstenberg in which the erosion damage was defined by specimen weight loss, plots of weight loss against impact velocity for steel showed a sharp upward trend at velocities above 680 mph (1000 ft/sec). At speeds of 820 mph (1200 ft/sec) these same steel specimens were rapidly cut through.

Wahl and Beal on their "whirling-arm" tests found that with a uniform water drop size, 2 mm methyl-methacrylate plastic (Plexiglas) at an impact velocity of 250 mph required 24 hours to initiate erosion while at 500 mph the same amount of erosion damage took place in twenty-five seconds.

In the same series of tests at 250 mph, soft aluminum (1100) showed erosion in 15 hours and at 500 mph similar erosion damage in 10 minutes.

Wahl, Ref. 22, from his experiments generalized that the time required to produce a given amount of erosion for most types

of materials is inversely proportional to some high power of the impact velocity.

2. Water Droplet Size

Both the water drop shape and size were found to be important elements in the amount of erosion damage produced. Brandenberger and deHaller, Ref. 30, using the wheel and jet apparatus varied the shape of the water drop by using flattened and oval shaped water jets. Using steel specimens, they observed that using drops of similar size, that with flattened droplets the erosion was more severe than with oval shaped drops.

However, the size rather than the shape of the impinging water droplet has a vastly greater effect on the amount of erosion damage. The importance of drop size was observed and noted by Honegger and deHaller, Refs.28 and 29, in which they found that large drops (8 mm diameter) will cause erosion at considerably lower collision velocities than small drops (2 mm diameter).

It seems probable that the difference in erosion damage could be related to the droplet size through the impact pressure. Impact pressures calculated by Vater and Honegger are not sufficiently high to explain the erosion damage caused by various sized drops. This inability to experimentally verify the impact pressure calculations is attributed by Honegger to the fact that the pressure distribution over the surface area struck by droplets may not be uniform (an assumption that is made in calculations of impact pressure).

Beal and Wahl conducted tests on the "whirling-arm" tester employing artificial rainfall of 3 inches/hour intensity, in which two average drop size diameters were investigated. In one case, the

rain drops had a uniform droplet diameter of 1.9 mm and in the second case the droplet diameters were 2.5 mm.

At a velocity of 500 mph using aluminum test specimens, the rate of erosion was 2.5 to 3 times greater **with** larger droplets, (2.5 mm) than with the smaller drops (1.9 mm).

There is no published experimental data on the erosion damage of droplets smaller than approximately 500 microns at impact velocities of approximately 400 mph. Erosion damage takes approximately 5 times as long to initiate for droplets of this diameter as compared to 2 mm droplets.

From the meager experimental data on the rate of erosion at speeds above Mach 1, it is impossible to extrapolate the erosion damage caused by water droplets having a diameter in the micron range.

3. Time

Honegger and deHaller in their experimental work prepared graphs of weight loss as a function of the number of impacts **or** the time of exposure to impact.

After an initial period, in which the onset of erosion is delayed, the weight loss of a specimen increases at a slow rate, then becomes greater, then finally decreasing again.

This behavior is explained by the fact that as long as the surface of the material is smooth, it is not degraded by the impinging drops. As soon as small pits occur in the surface the weight loss increases slowly, but as soon as the entire surface is roughened the weight loss due to erosion increases rapidly. After the roughness

has reached some depth, a layer of water tends to remain spread over the whole surface and this layer of water tends to reduce the effect of further water drop impacts, causing a decrease in the rate of erosion.

4. Design

It has been shown in experiments by Wahl, Refs. 20 and 21, that the severity of rain erosion damage can be reduced by changing the angle of rain drop impingement. Erosion is at a maximum when the droplet impingement is normal to the surface moving at high velocity. As the angle of drop impingement with the moving surface is reduced, the extent of erosion damage is rapidly decreased. Wahl states from his work that at angles of impact, less than 15°, the rate of erosion approaches zero.

Thus the more glancing the rain drop impacts can be made to be in the direction of flight, the lower the amount of erosion damage.

A theory which has been advanced but which has not been experimentally verified is that at supersonic speeds the shock wave will tend to break up large rain drops into mist-like drops before the large drops can impact the surface behind the shock wave, Ref. 32.

A vehicle moving at supersonic velocity through air is accompanied by a shock wave. If the leading edge of the vehicle is a sharp point, the shock wave is attached to it; if the leading edge is blunt, the shock wave is detached and is separated from the leading surface of the vehicle by a zone in which air is moving ahead of the vehicle. The width of the zone by which the detached shock wave

is separated from the vehicle depends on the radius of curvature of the leading edge and the velocity at which it is moving. The width of the shock wave itself is vanishingly small.

The existence of this phenomenon may prove to be of considerable importance to the problem of rain erosion of aircraft moving at supersonic velocities, for the following reasons. If a water drop is shattered into a multitude of very small droplets by the shock wave in the zone by which the shock is separated from the leading edge of the vehicle, and if this fragmentation will have time to occur before the leading edge collides with a stationary water drop in its path, the problem of erosion by rain may be much less serious at supersonic velocities than at subsonic velocities. If the water drop should prove to be completely atomized before it reaches the surface of the vehicle, there would be no rain erosion problems at these supersonic velocities. To determine whether or not such an escape from the problem of rain erosion at supersonic velocities is possible, it will be necessary to conduct experimental tests or flights.

C. Current Materials

The resistance to erosion of a particular material is a function of many interrelated properties such as surface finish and hardness, tensile, compressive and impact strength, flexibility, elasticity and work hardening characteristics.

Many studies have been conducted on metals, glass, ceramics, plastics and rubbers in various forms and combinations trying to

pinpoint a property or group of properties that could be used as a criterion for predicting rain erosion resistance.

The studies carried out by a large number of investigators on the resistance to water drop erosion of various types of materials has been summarized and evaluated in a very comprehensive report by Engel, Ref. 12, as well as by Lapp and Wahl, Ref. 33.

The results of this summary by Engel indicates that because the characteristic properties of materials (for example coatings, metals and plastics) are different, there are as many different erosion damage processes as there are broad groups of materials properties in various types of materials.

From the experimental studies by Wahl and Lapp, two schools of thought regarding the solution to the high speed rain erosion problem have been evolved. One group believes the soft rubbery type materials are the answer and another group backs the hard rigid materials.

A material that yields like rubber under the blow that results from collision with a liquid drop has the advantage of being a pressure-reducer for the blow. When the impact pressure that results from collision with the liquid drop is reduced, the velocity of the radial flow of the liquid of the drop, which is driven by the impact pressure, is also reduced. Because the radial flow velocity is re-duced, the shear stress that it exerts, which varies qualitatively with the radial flow velocity, is likewise reduced.

Material that undergoes rubber-like yield needs to have strength properties of sufficiently high value to withstand the shear stresses

of a single impact but must also recover fast enough to be able to absorb the stresses of rapid additional blows. To be a practical rain erosion-resistant material the rubber must, furthermore, not lose its ability to absorb repeated impact stresses over long periods of exposure.

Hard, rigid materials that do not display drastic rubber-like yield as a result of collision with a liquid drop do not mitigate to any notable degree the impact and shear stresses that the colliding drop exerts. To be erosion resistant, rigid materials must therefore be able to withstand these combined stresses. Whether or not they can withstand the unmitigated stresses depends on their yield or on their fracture strength. If the relative impact velocity between the solid material and the liquid drop is increased to an extremely high value all the known hard rigid materials will be found to fail at the point where their yield or fracture strength is exceeded, i.e. they will either yield with plastic flow or they will shatter.

Metals undergo permanent plastic flow when their yield strength is exceeded. In the case of a soft metal such as 1100 aluminum the depression in the surface caused by a single collision with a water drop at high subsonic velocity is barely perceptible but the beating action of repeated droplet impacts produces, by plastic flow, a number of fine pit-like depressions resulting in a general unevenness of the surface that appears to play a role in increasing the rate of erosion damage of the material.

In general the most pressing current problem in the area of rain erosion resistant materials is concerned with radomes and the leading edges of supersonic aircraft wings and helicopter rotor blades.

In the case of radomes, ceramics such as Pyroceram, high density alumina and fused silica have been found to be the most satisfactory under current service conditions. These materials are resistant to relatively high temperatures and generally withstand erosion up to Mach 2 for relatively long periods. The major problems associated with these materials are their extreme brittleness, poor resistance to impact and generally unsatisfactory methods of attachment to metal structures.

The problem of preventing erosion of the leading edge of wings and control surfaces of supersonic aircraft employing refractory metals can be reduced by employing dense ceramic coatings such as aluminum or silicon carbide.

However, practical processing methods must be developed for applying these coatings to large structures before this approach is considered satisfactory.

The use of polymeric or elastomeric coatings for radomes, leading edges of aircraft and helicopter rotor blades possessing erosion resistance to velocities approaching Mach 1, has been generally solved by the use of neoprene coatings produced by Gates Engineering Company and Goodyear Tire & Rubber Company. The data on the rain erosion resistance of neoprene has been reported by Engel and Wahl, Refs. 15 and 25. The successful use of a polyurethane rubber

Estane as a resistant coating has been reported by Kageorge of
B. F. Goodrich Co., Ref. 34.

These organic coatings are not satisfactory for use at tempera-
tures above 250°F.

Two reports have been previously issued which summarize the
state-of-the-art of rain erosion resistance of materials, Refs. 12
and 33. These reports are still useful in that the materials in-
formation has not been superseded by new data.

While the materials discussed above are marginally suitable
for current subsonic aerospace vehicle applications, a great deal of
research and development effort will be needed to produce new mate-
rial that will be erosion resistant if future requirements for super-
sonic aircraft and advanced missiles are to be achieved.

D. Test Methods

The development of aerospace vehicles such as transports and
missiles that will operate at supersonic speeds in the Earth's at-
mosphere has created a need for detailed knowledge of the rain
erosion phenomena and the erosion characteristics of engineering
materials at flight speeds above Mach 1.

Because of the lack of quantitative data on the rain erosion
rates of materials at supersonic velocities a number of test facil-
ities have been set up and experimental tests have been conducted
by various organizations in the United States and other countries.
This section of this report summarizes available information on the
various types of test equipment and facilities that are in current

operation at subsonic and supersonic velocities and to summarize
the results of known studies that have been conducted on the problem
of rain erosion during the last five years.

The information of greatest importance to the engineer design-
ing supersonic vehicles that will fly through rain is the length of
time a given material will resist erosion damage at various veloc-
ities.

The obvious method for obtaining experimental data on the rain
erosion resistance of various types of materials is to mount them
on the exterior of the aerospace vehicle and fly through rain. This
method of testing is relatively expensive and has an inherent dif-
ficulty in that the components being tested or the vehicle may be
lost due to severe structural damage.

1. Flight Tests

As previously noted, Refs. 1 and 2, actual flight tests to
study the pheonmenon of rain erosion at subsonic speeds were carried
out by the United States Air Force and by Cornell Aeronautical Lab-
oratory, and the fact was established that aluminum leading edges
and plastics exhibited serious erosion after exposure to rainfall
of moderate intensity.

During the early part of 1961 the Flight Test Group of Aero-
nautical Systems Division of the Air Force in cooperation with
National Aeronautics and Space Administration carried out flight
tests in which an F106 airplane was flown through thunderstorms at
supersonic and high subsonic speeds to determine the response of
supersonic aircraft to air loads and erosion.

Although the aircraft suffered no major structural damage, such items as rivet heads and the leading edge of the wings, the aluminum nose cone, the cockpit canopy frame and the plastic laminate antenna covering showed severe erosion due to water drops and/or tiny ice crystals at flight speeds of Mach 1.6 at 40,000 ft altitude, Ref. 35.

2. Laboratory Tests

Techniques which are currently employed for determining the erosion resistance of materials, do not exactly simulate the actual service conditions experienced during flight but which are considered suitable for comparative evaluation, are as follows:

    a. Whirling Arm

    b. Ballistic Techniques

    c. Rocket Sled Tests

    d. Wind Tunnel Tests

    a. "Whirling Arm"

The "whirling arm" test equipment consists of a blade or propeller which rotates in a horizontal or vertical plane. Specimens of various airfoil geometrics are mounted on the leading edges near the blade tip. The blades with the mounted specimen are rotated through an artificial rainfield usually consisting of uniform water drops, ranging from 0.1 to 1 inch per hour. In general most of these tests operate at speeds up to Mach 1.

The practical limitations to the use of the "whirling arm" type of equipment are the high power requirements, the large

centrifugal forces imposed upon the propeller blade as well as the specimens and the inability to obtain reproducible rain erosion rates on a specific material at a given velocity unless the rain drops are spherical in shape and extremely uniform in diameter and concentration.

A number of these "whirling arm" test apparatus have been described in the literature. These test rigs, and their location are as follows:

United States:

1.   B. F. Goodrich Company Research Laboratory, Brecksville, Ohio, Ref. 34

Maximum velocity of testing 600 mph.   Fig. 1 and 2

2.   Cornell Aeronautical Laboratory, Buffalo, New York, Ref.3

Maximum velocity of testing 600 mph.   Fig. 3

3.   University of Cincinnati, Dept. of Mechanical Eng., Cincinnati, Ohio, Ref. 36

Maximum velocity of testing 600 mph.

4.   Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio, Ref. 38

Maximum velocity - 6 ft. blade   Mach 1, Figs. 4 and 5

-20 ft. blade   Mach 2.2

Figs. 6 and 7

England:

5.   Royal Aircraft Establishment, Farnborough, England, Ref.37

Maximum velocity - 500-600 mph.

West Germany:

  6. Dornier System GmbH - Immenstaad, Germany, Refs. 39
     and 40.

     Maximum velocity - Mach 1.4

  b. Ballistic Techniques

     Ballistic techniques that have been employed involve
the use of air pressure or gun powder, a gun barrel or blast tube
and a projectile or sabot to carry the specimen or the water drop.

     In early work at Convair, Ref. 19, a 57mm cannon was
used to propel a projectile carrying a small cone shaped specimen
through a 1500 ft. rainfield. The recovery system consisted of a
small parachute which was unfurled after a specific delay period.
This was the first device that attained testing velocities approach-
ing Mach 2.

     Later work involved the use of blast tube and sabot
to carry the liquid drop (water or mercury) which impacted the speci-
men surface, Ref. 19. While supersonic velocities could be obtained
with this ballistic device it was limited by the fact that only one
impact per firing was obtained and it was difficult to obtain re-
peated impact in the same area on the test specimen.

     A similar device has been described by investigation
at the Royal Aircraft Establishment, Farnborough, England, Ref. 41.
In this apparatus the specimen is in the projectile which impacts a
single drop of water held in the flight path by a very fine web.
Velocities approaching Mach 3 are obtained. Here again only one

impact per firing is obtained and it is difficult to obtain repeated impacts on the same area of the specimen under test.

Another ballistic technique that employed a pellet of polyethylene instead of a water drop has been employed to evaluate ceramic materials by investigators at Applied Physics Laboratory of John Hopkins University, Ref. 42. Velocities approaching Mach 2 were obtained. A recent study by Bowden and Brunton, Ref. 64, and Bowden and Tabor, Ref. 71, describes a method for projecting a single small cylinder of water at velocities greater than 6000 ft/sec against a stationary solid target. Here again only single impacts are obtained for each firing. This type of test may be considered as a static type of test in which the specimen is allowed to recover after each impact and is not subjected to rapid repeated impacts which may have a fatigue effect on various materials.

c. Rocket Sled Tests

Rain erosion tests at supersonic velocities in which a vehicle or sled running on a track is accelerated to the desired velocity by means of solid propellant rocket engines then passes through a calibrated rainfield have been successfully employed for evaluating the rain erosion characteristics of coatings, plastics and ceramic materials. During 1955 and 1956 tests were conducted on Bomarc missile radomes at Edwards Air Force Base Research Sled Test Facility at velocities slightly above Mach 2, Ref. 19. During 1956 the rainfield was extended from (2000 to 3000 ft) and tests were conducted for Raytheon, Ref. 43. This facility, however, is no longer in use.

Other sled test facilities currently in use are located at:

1. Pendine, England - Royal Aircraft Establishment.

2. Holloman Air Force Base, New Mexico - Air Force.

3. Naval Ordnance Test Station, China Lake,

   California - Navy

The sled facility at Pendine, England is operated by the RAE. Farnborough has a track length of 3000 ft. passing through a 500 ft. rainfield. The average water drop size ranges from 1.2 to 2.8 mm with a mean intensity of 5.8 inches per hour. The maximum velocity is approximately Mach 1.5, Ref. 44.

The sled for supersonic rain erosion studies at Holloman Air Force Base, New Mexico operates on a monorail of 35,000 feet in length. The facility has a 6000 ft. long artificial rainfield. The nominal velocities obtainable range from Mach 1 to 2.5, Ref. 45. The rainfall rate approaches 6 inches per hour with a 2-3 mile/hour wind. The water droplet size ranges from 1 to 2 mm in diameter, Ref. 46.

The Supersonic Naval Ordnance Research Track (SNORT) at China Lake, California employs a sled operating on a monorail of 21,500 feet in length. The rainfield is 2,500 ft. long. The rain intensity can be varied from 2 to 4 inches per hour. Normal test conditions were nominally 2 inches/hour intensity with a medium water droplet size of 2 mm. The maximum velocity obtainable is approximately Mach 3, Ref. 47.

d. Wind Tunnels

A number of investigators, Refs. 48 and 49, have considered techniques for injecting water droplets, of desired size,

at practically zero velocity into an air stream in a wind tunnel and accelerating the drops to supersonic velocity. Most of these approaches have been shown to be impractical due to the length of the tunnel required. Another approach is to inject the water into a wind tunnel at high velocity, but in general these techniques have been unsatisfactory since slugs of water and not spherical droplets are obtained.

Under a Navy sponsored program, Ref. 50 an injection device was developed by investigators at Mithras Inc. in which the slugs of water are injected into a venturi at a given pressure. By careful control of the relative velocity between the injected water and the local air stream in the venturi, water drops of **relatively** uniform droplet sizes are accelerated to velocities ranging from Mach 1 to 2. The equipment and details are outlined in the classified report, Ref. 50.

3. Extrapolation of Data

The information of greatest interest to the designer of supersonic vehicles that will fly through rain is how long will a given material resist erosion damage due to repeated impacts of water droplets at extremely high velocities.

It is extremely costly and experimentally difficult to evaluate the erosion resistance of structural materials because of the problems involved in accelerating either water drops or specimens to the velocities in question.

To bypass these difficulties, the use of droplets of high density liquids instead of water droplets have been explored as a means of predicting the comparative damage that would be caused by the collision of a test specimen with a water drop at very high velocities with the damage caused upon the same test specimen with a high density liquid drop at much lower velocities, Ref. 19.

To develop this idea into a reliable test procedure, Engel described methods for correlating the impact-velocities-for-equal-damage employing single drops of mercury at low impact velocities to predict failure due to single water droplet impacts at high velocities, Ref. 14. Figure 19 is a graph demonstrating this equal-damage comparison for 1100 aluminum.

In rain erosion tests of 600 mph at Cornell, Lapp and Wahl found that of the ceramic materials, high density alumina (Al_2O_3) had a very great resistance to rain erosion, Ref. 27. With this in mind, Engel conducted tests on hot pressed 1/8" thick alumina disks. In these tests it was observed that velocities in excess of Mach 1.3 (1,400 ft/sec) were required to damage the alumina specimens when 2 mm mercury droplets were used, Ref. 17.

A theoretical extrapolation suggests that supported high density alumina leading edges 1/8" thick can be expected to survive collision with water droplets of 2 mm or smaller diameter without damage up to velocity of Mach 10 (approximately 11,000 ft/sec.).

In summary, it can be stated that selected ceramic materials with a high impact and compressive strength and high strength re-fractory metals will undoubtedly provide a practical solution to

the rain erosion problem at supersonic flight velocities up to Mach 3. This opinion is based upon Engel's theoretical analysis and Wahl's experiments at 600 mph in 1 inch/hr. rainfall in which incipient erosion occurred on hard metals and ceramics only after many hours of exposure.

E. Recent Rain Erosion Studies

A number of organizations have conducted experimental programs during the last five years to obtain specific information on the rain erosion problem and to assess the characteristics of specific coatings, plastics or ceramics, exposed to simulated rainfall at supersonic velocities. A brief review of these tests and results are described below.

1. Drop-Size Distribution

An excellent study that is pertinent to the problem of rain erosion was conducted by Hardy and Dingle, Ref. 51. The program, sponsored by the Air Force Cambridge Research Laboratories, is concerned with raindrop-size distribution as a function of altitude and also describes a photoelectric raindrop-size spectrophotometer which was developed and calibrated.

2. Droplet Fragmentation

Reynolds in his report on supersonic sled studies, Ref. 46, discusses briefly the results of tests on radomes 6.5 inches long, 7.5 inch diameter with a spherical nose radius of 2.35 inches. In this report he concludes that droplets less than 1 mm in diameter were fragmented or reduced to mist by shock waves as predicted by

Engel, Ref. 32, but that droplets of 1.0 to 3 mm in diameter impacted various locations on the radome causing erosion under the particular conditions of the test. Methods of causing fragmentation of water drops in the zone behind shock waves caused by spherical bodies moving at supersonic velocity through water droplets has been studied and described by several investigators, Refs. 32 and 50, and is worthy of consideration for designing supersonic vehicle components with reduced rates of erosion.

3. Coating Tests

Tests of rain erosion resistant coatings were conducted on a "whirling arm" test apparatus at velocities ranging from approximately Mach 1 to 2 early in 1962 by Flight Engineering Group at Wright-Patterson Air Force Base, Ref. 52. The results of these tests indicate that none of the Gaco, Goodyear or Epoxy coatings up to 0.030" in thickness were satisfactory for periods greater than 10-30 seconds at the velocities employed.

4. Radome Tests (Sandia Corporation)

Rain erosion tests were conducted for Sandia Corporation on small radomes of ceramic, epoxy-fiberglas, neoprene coated epoxy-fiberglas, phenolic fiberglas with a ceramic tip, at Holloman AFB rocket sled facility during 1962 and 1963, Refs. 45 and 46. These tests were conducted at velocities ranging from Mach 1 through Mach 2.5. High speed photographs were taken and visual analysis of the results were made. Curves of the average erosion rate as a

function of velocity for epoxy-fiberglas laminated radomes and neoprene coated epoxy-fiberglas radomes were prepared, Ref. 46. The ceramic radomes did not show progressive erosion damage but generally failed by fracturing after random periods of exposure to rainfall at various velocities.

5. Ceramic Radomes (General Dynamics)

Several types of ceramic radomes were prepared and tested for rain erosion resistance on SNORT at Naval Ordnance Test Station, China Lake, California, for General Dynamics at maximum velocities of Mach 2.7 early in 1963. These tests indicated that pointed fused silica radomes of certain wall thicknesses were satisfactory. Two hemispherical glass fiber reinforced plastic radomes from NADC with and without a 10 inch spike were tested at average velocity of Mach 2. The plastic radome with the spike had less erosion than the radome without the spike, Ref. 53.

6. Supersonic Tests in Germany

At Dornier System - GmbH research on supersonic rain erosion tests have been conducted since 1960, for the German Ministry of Defense. H. Busch and G. Hoff have described the "whirling-arm" apparatus they have used. This test equipment reaches a maximum speed of Mach 1.4, Ref. 40, which is stated to impose extremely high G loads on the specimen. The rain drops are produced by means of a disc rotating at various speeds. Water runs on the disc and water drops are centrifuged off the edge. A strobe light and high

speed camera is used to monitor the erosion phenomenon. The information on the materials evaluated are not specific, but are stated to cover major metal, galvanized and organic coated metal surfaces, polymeric materials and glasses. General details are outlined in an article by Wetmore, Ref. 39.

Early in May 1965 a symposium, co-sponsored by RAE of Farnborough, England and Dornier System GmbH was held in Meersburg, West Germany. References 54 through 70 outline the papers presented at this symposium. These papers review in great detail the work conducted at supersonic speeds by Dornier System.

Most of the tests on the rain erosion resistance of various materials were conducted at Mach 1.2 (920 mph) employing a single counter-balanced test blade of 120 cm (4 ft.) in length and a typical water droplet size of 1.2 mm in diameter. The rainfield is not continuous in Dornier's current setup since it consists of eight hypodermic needles spaced at 45° intervals on a 240 cm (8 ft.) diameter water supply line.

The rain erosion test specimens are flat surfaced cylindrical sections 1.5 cm in diameter (0.6") diameter by 0.5 to 1.0 cm in thickness (0.2" to 0.4" thick). The area of the circular specimens sweeping through the water drops is 1.76 cm^2. The rainfall density is defined by Dornier as the ratio of the water volume to the volume of the space swept by the specimen as it rotates in a horizontal plane. This ratio (mm^3 H$_2$O/mm^3 air) is reported to be 10^{-5} and is constant for most of the studies conducted by Dornier.

This definition implies that 100 percent catch is obtained (i.e. the percentage of the water droplets impacting the flat faced specimen of 1.5 cm diameter as it rotates through the falling water drops of 1.2 mm at a speed of Mach 1.2 is 100%). Based upon the analytical studies of Engel, Ref. 32, and the experiments of Dittman and Wahl, Refs. 19 and 21, this high percentage of catch for small drops is questionable due to the air turbulance caused by a flat specimen moving at supersonic speeds.

The measurement of weight loss due to erosion noted by Langbein, Ref. 55, is shown to be a linear function of time of exposure to rainfall for polymeric materials. In his work, Wahl, Refs. 21 and 22, noted that loss in weight of polymeric materials such as methylmethacrylate did not proceed at a uniform rate because the erosion process consisted of the chipping out or erosion of particles of random size. Reproducible results with an airfoil shaped specimen of a standard polymeric material such as methylmethacrylate were not attained in the whirling-arm test setup at Cornell, Ref. 21. Undoubtedly if large numbers of samples were eroded and the data concerning the loss in weight treated statistically a precise graph of the loss in weight as a function of time would be attained. The usefulness of the data of the average weight loss obtained in this statistical study in predicting the probable service life of a material as compared to the data obtained by studying the time to initiate erosion over 50% of the airfoil surface of a smaller number of samples is debatable.

The rain erosion resistance of metals, coatings, polymeric, glass and ceramic materials and the investigation of the mechanics of erosion and such parameters as the rate of erosion as a function of speed and the angle of incidence of drop impact are all reviewed in detail in Refs. 54 through 61.

The reported results generally confirm the previously presented data by other investigators such as Engel, Wahl and Dittman and a similar list of the comparative erosion resistance of various types of materials has been compiled in the studies reported by Dornier.

One of the areas that has been explored to a greater degree in the Dornier studies as compared to the studies in the United States is the investigation of the influence of hardness and grain size of metals and metal alloys in their rain erosion resistance. Based upon these studies the investigators at Dornier were of the opinion that the best approach to improving the rain erosion resistance was to increase the hardness of the metal and decrease the grain size. The order of magnitude of improvement obtained was not specifically stated.

F. Recommendations

Anticipating the need for improved rain erosion resistant materials for supersonic aircraft and advanced missiles which cannot be taken off the shelf but will require three to five years of research and development effort to achieve, the following actions are recommended:

1. Expand our knowledge of the phenomenon of rain erosion of aero-space materials particularly at supersonic velocities. This would be accomplished by the development of a laboratory test method for the comparative evaluation of the relative rain erosion resistance of materials under controlled conditions, at velocities ranging from approximately five hundred mph to fifteen hundred mph (Mach .67 to 2.0) and conducting additional analytical and experimental studies of the mechanism of water drop erosion.

2. Priority should be placed on the development and operation of rain erosion test equipment employing uniform continuous rain-fields and capable of continuous testing of materials for periods up to one hour at velocities ranging from subsonic to supersonic.

3. Utilizing the basic studies that have been initiated on the mechanism of rain erosion expand this work to predict the probable life of various types of materials at supersonic **veloc-ities** and experimentally verify the predicted life at various velocities.

4. Employing the data obtained from these analytical and experimental investigations identify the factors or properties which influence the rain erosion resistance of materials. This information would be useful in the development of engineering materials with improved properties. It is believed that this approach would be more efficient than empirical evaluation of all types of materials.

5. Current known information on the service life of various types of structural materials such as plastics, metals and ceramics at 500 mph should be expanded to supersonic speeds. This information is sorely needed for the design of advanced supersonic aircraft.

6. Because a large amount of data have been generated under relatively standard conditions at 500 mph and a one inch per hour rainfall rate employing a uniform rainfield consisting of droplets of 2 mm diameter, it is recommended that these data be correlated with supersonic test data obtained on any newly developed test apparatus.

7. More objective methods for measuring and comparing the erosion rate of various types of materials should be developed. The present method which depends on visual observation of the initiation of erosion on a surface is reproducible. Techniques for determining the rate of erosion by measurement of the loss in volume or weight loss have proven unsatisfactory with airfoil shaped specimens since the amount eroded from a given material usually is a random process.

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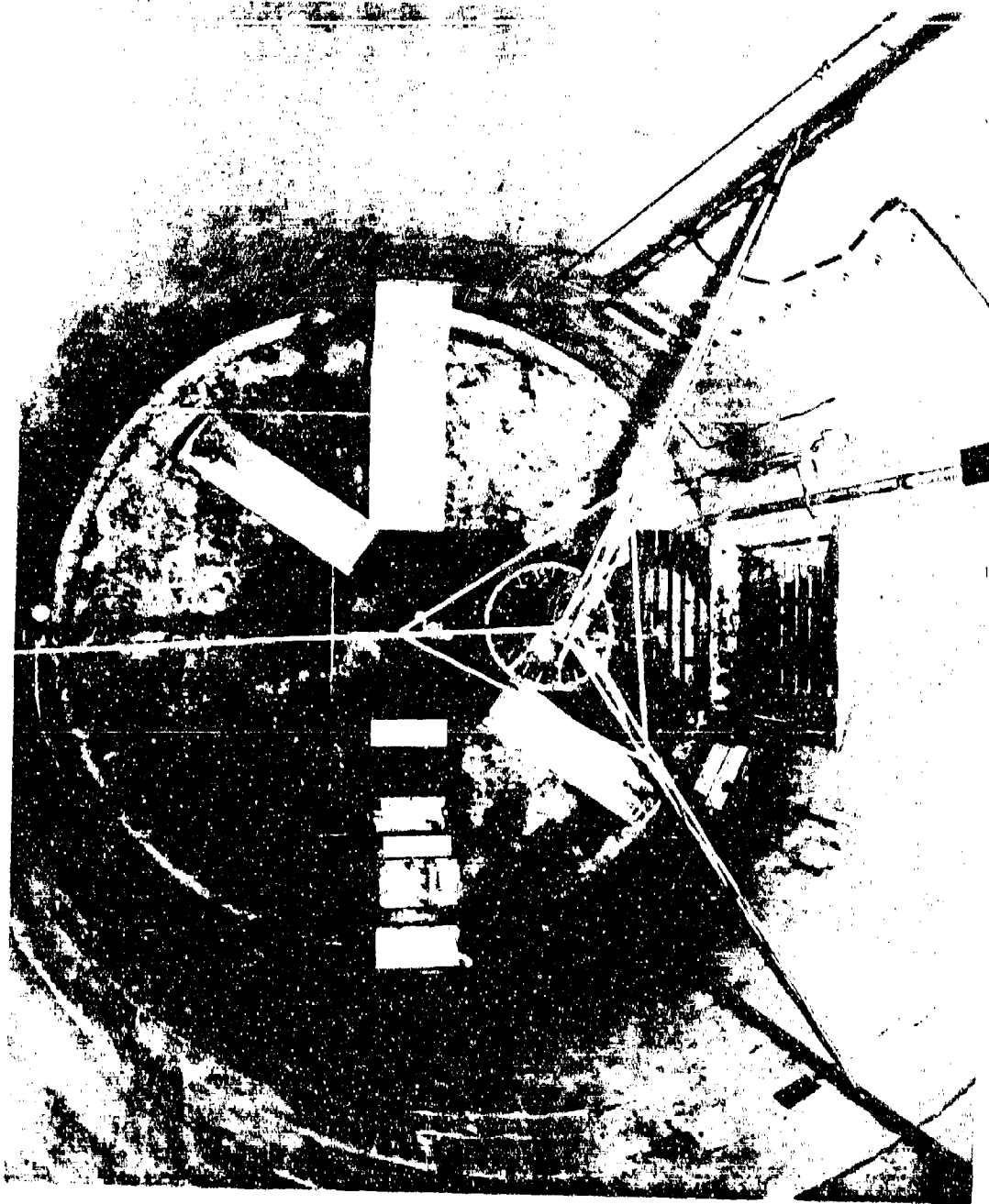Figure 1. B. F. Goodrich Test Facility Showing Motor, Blade and Sample

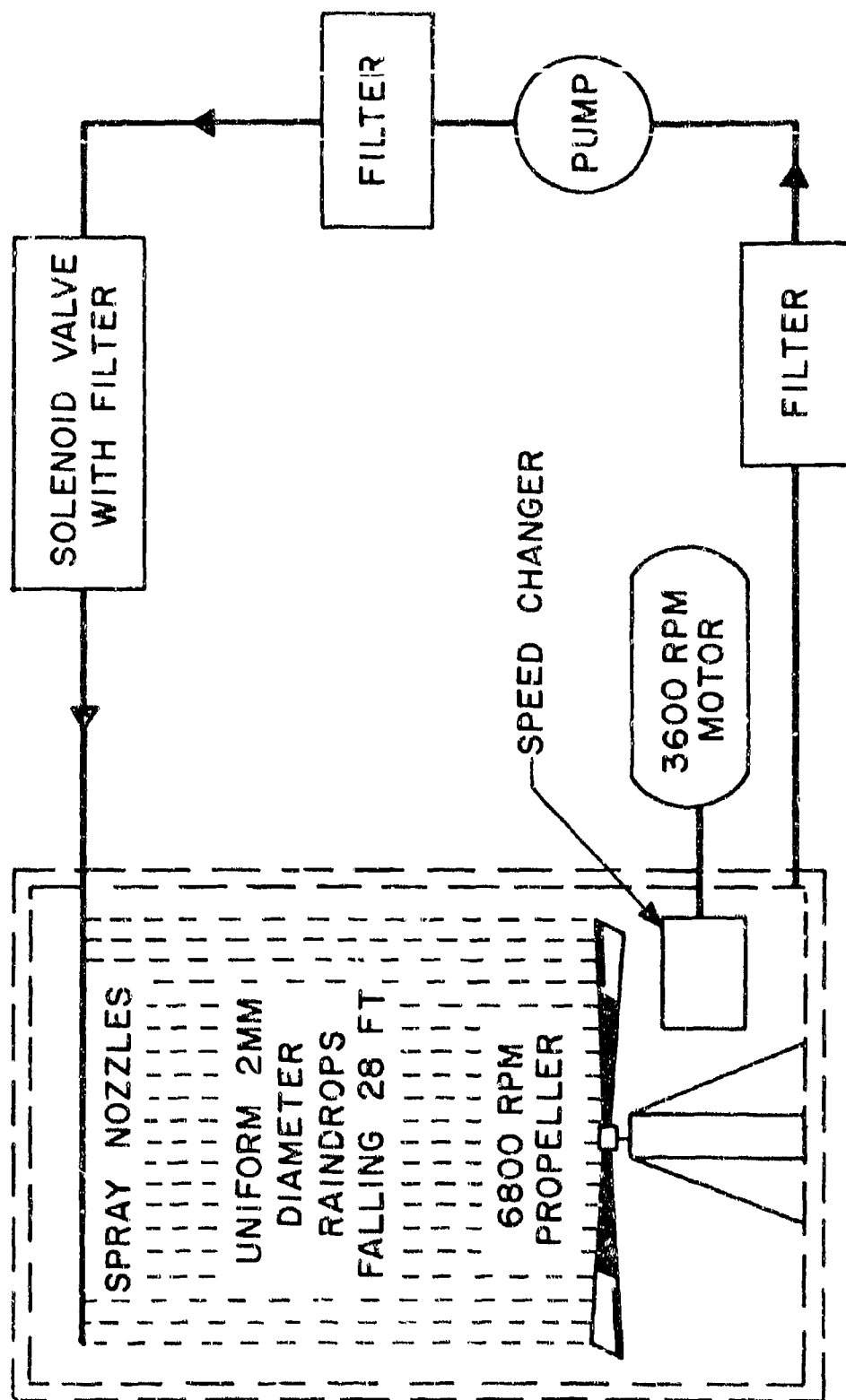Figure 2. B. F. Goodrich Rain Erosion Test Facility

Figure 3. Specimens are Mounted on a Propeller and Whirled at 500 mph
Through Simulated Rainfall of 1-in./hr.

Figure 4. 6 Foot Diameter Rain Erosion Facility Inside of Test
Enclosure Showing Spray Ring, Whirling Arm with Test
Specimen Installed, and Periscope Tube.

Figure 5. 6 Foot Diameter Rain Erosion Facility Inside of Test
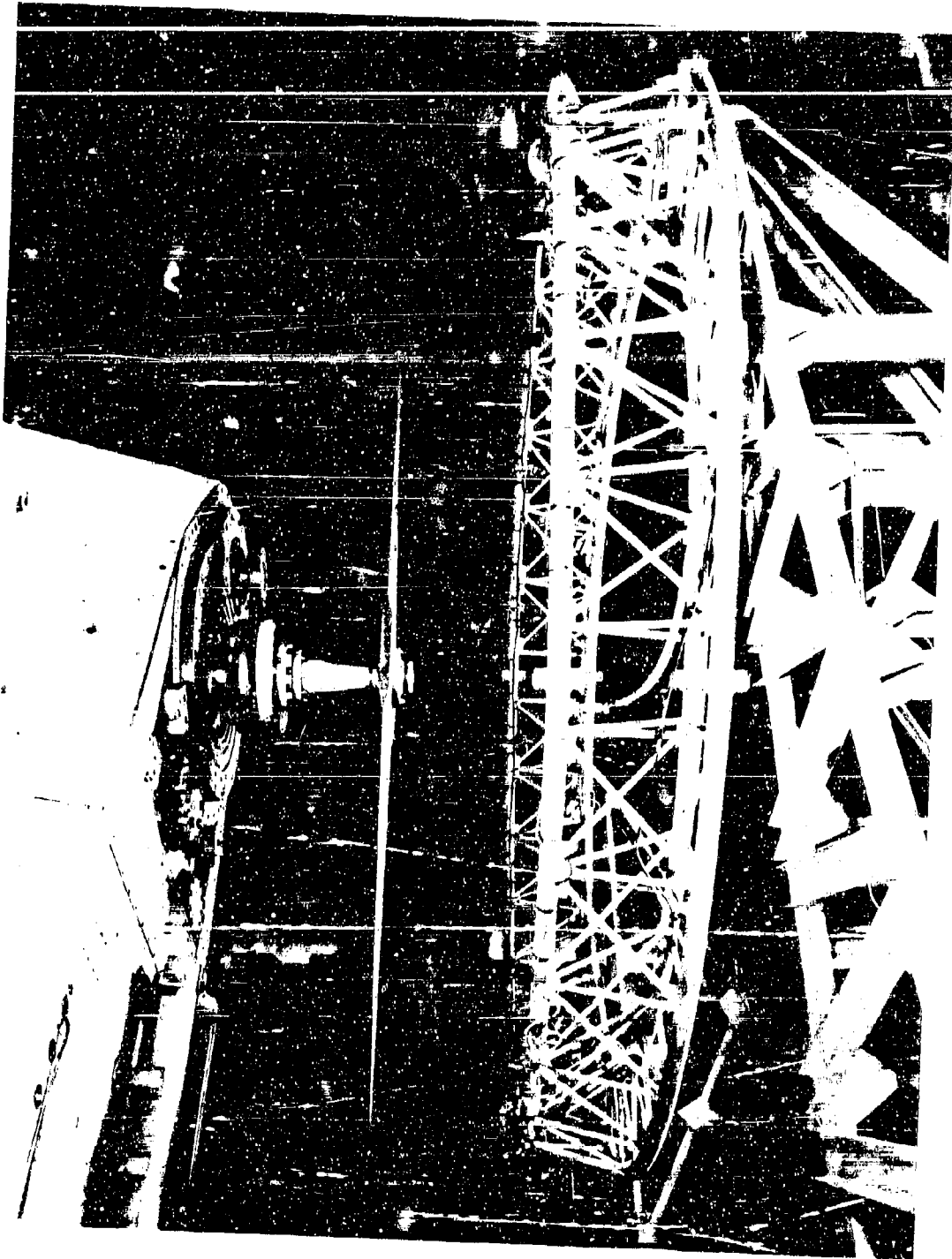Enclosure Showing Spray Ring and Whirling Arm

Figure 6. 20 Ft. Diameter Blade & Spray Ring at WPAFB

Figure 7. Front View of Supersonic "Whirling Arm" at WPAFB

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13. ABSTRACT

A comprehensive state-of-the-art survey in the field of rain erosion protection, evaluation and simulation has been completed. Past efforts in all phases of rain erosion research, both subsonic and supersonic are reviewed. Descriptions of evaluation facilities now in operation and summaries of past materials research are also included.

Recommendations for the improvement of laboratory simulation of high speed rain erosion protection techniques and the direction for new materials development are indicated.

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